(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 205 659 A2

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
15.05.2002 Bulletin 2002/20

(51) Int Cl.⁷: **F02M 25/00**, F02B 47/02, F02B 3/06

(21) Application number: **01309098.0**

(22) Date of filing: **26.10.2001**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: **03.11.2000 FI 20002425**

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(54) **Method of reducing nitrogen oxide (NOX) emissions of super-charged piston engine**

(57) A method of reducing nitrogen oxide (NOx) emissions in a supercharged piston engine (1) comprising increasing the pressure of intake air by means of a supercharger (2) and feeding water (4,4',8) into the compressed intake air before leading the intake air to the engine so as to increase the humidity of the intake air. The temperature of the intake air supplied to the engine is controlled by a control arrangement controlling the operation of a heat exchanger (5,5') and/or the injection of water into the intake air based on the measurement of conditions of the intake air. The invention also relates to an arrangement for reducing nitrogen oxide (NOx) emissions of a supercharged piston engine (1).

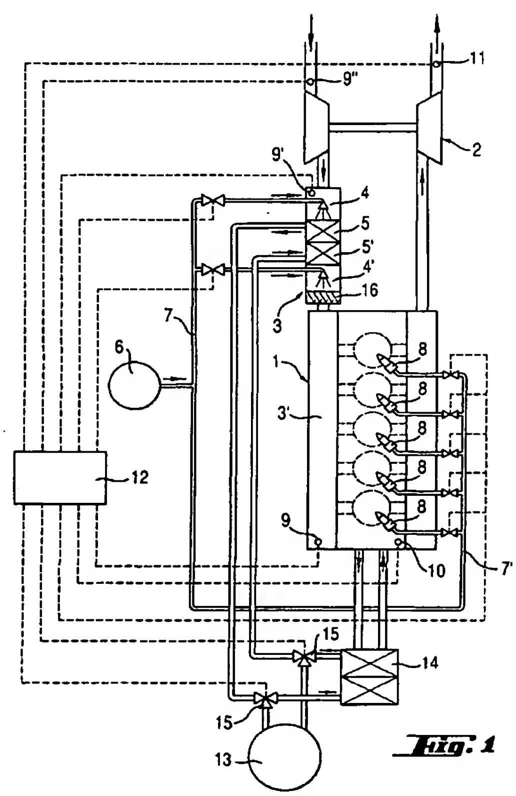

Fig. 1

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Printed by Jouve, 75001 PARIS (FR)

Description

[0001] This invention relates to a method of reducing nitrogen oxide (NOx) emissions of a supercharged piston engine, the method being of the kind comprising compressing intake air to produce compressed intake air, introducing water (4,4',8) into the compressed intake air to increase the humidity of the intake air, and supplying the humidified and compressed intake air to the engine. The invention relates also to a supercharged piston engine of the kind comprising cylinders, a supercharger for compressing intake air, conduit means connecting the supercharger to said cylinders for supplying compressed intake air from the supercharger to said cylinders, and a nozzle arrangement associated with the conduit means for introducing water into compressed intake air passing through the conduit means to said cylinders. In this specification the term "water" is intended to include water or water-containing solutions in liquid or atomised form.

[0002] Nitrogen oxides (NOx) are formed at high combustion temperatures in the cylinder of a piston engine and are discharged to the atmosphere along with exhaust gases. Due to the harmful effects of nitrogen oxide emissions it is a general aim to reduce these emissions.

[0003] It is known that the addition of water in the combustion process and in combustion air reduces the formation of nitrogen oxides. This phenomenon is based, among other things, on the cooling effect of the added water. In practice, the addition of water into the combustion process of piston engines has been realized in two alternative ways; the water being fed either directly to the combustion chamber of the cylinder or via ducting carrying intake air to the engine.

[0004] In US-A-5758606 there is disclosed a method of feeding water into compressed intake air of a supercharged engine after the supercharger. The water is first heated by heated "cooling" water of the engine and is fed into a separate humidification tower in which atomised water evaporates. This known arrangement is impractical due, among other things, to the space requirements of the humidification tower. It also carries a certain safety risk because large humidification towers operate at high pressure.

[0005] Injecting water and intake air into the combustion chamber does not impair the shaft efficiency of the engine as such. However in certain circumstances the temperature of the intake air needs to be raised in order to raise the humidity of the intake air sufficiently to reduce the creation of nitrogen oxides and this in turn decreases the mass flow of the intake air and its oxygen content. The amount of water which can be introduced into the combustion chamber is, at most, the amount which remains in vapour form at the prevailing pressure and temperature of the intake air. Thus the amount of water that can be introduced with the intake air into the combustion chamber is limited by the saturation of the water vapour in the intake air. The amount of water required to be added is relatively high because part of the water may not be utilised because of continuous humidification during the scavenging stage of the cylinders when both the inlet and outlet valves are simultaneously open.

[0006] In EP-A-0683307 there is shown an apparatus for feeding water directly into cylinders of an engine, the feeding being dependent on the firing order of the engine. Water is injected during the induction or inlet stroke under the control of a control unit, which utilises engine speed, piston position and/or operating conditions of the engine as control parameters. The optimum distribution of water into the combustion chamber so that excess water is not injected and, on the other hand, so that a desired effect should be accomplished, is a problem with this known apparatus.

[0007] It is known as such to inject water directly into the combustion chamber by introducing the water together with the fuel or by alternating water and fuel injection with a common injector arrangement.

[0008] When water is injected directly into the combustion chamber, injection may also be achieved during the compression stroke, either before the actual combustion process and/or during it. However, although this injection moment is favourable with respect to the reduction in the formation of nitrogen oxides and to undisturbed power output, it is unfavourable with respect to shaft efficiency. This is because at the end of compression the pressure of the compressed air and/or the mixture of air and fuel decreases as a result of the water feeding, so that the engine must do such compression work which cannot be utilised in the expansion stroke. Another factor which decreases the shaft efficiency of the engine is the relatively high pressure, typically about 200 bar, required to feed the water into a cylinder which pressure must, of course, exceed the pressure prevailing in the cylinder at the moment of injection.

[0009] Direct water injection into the combustion chamber during the inlet stroke is favourable as such since, for example, a decrease of pressure in the cylinder is accomplished by the introduction of water. This facilitates the filling of the cylinder with air or with a mixture of air and fuel and thus decreases the work of the compressor, which is favourable with respect to shaft efficiency and power output of the engine. This phenomenon may be further enhanced by means of the present invention.

[0010] It is an object of the invention to provide an enhanced method of and arrangement for reducing nitrogen oxide emissions in a supercharged piston engine, which method is based on feeding water into combustion air, but in which drawbacks of prior art methods have been substantially eliminated. Specifically, an object of the invention is to provide a method and arrangement which, in addition to reducing nitrogen oxides, is advantageous with respect to shaft efficiency, power output and the required amount of water.

[0011] The objects of the invention are met substan-

tially as is disclosed in the ensuing claims 1 and 13.

[0012] According to an advantageous embodiment of the invention a method of reducing nitrogen oxide (NOx) emissions in a supercharged piston engine comprises increasing the pressure level of intake air by means of a supercharger from ambient pressure level to an elevated pressure level and feeding water into the intake air before leading the intake air into the cylinders of the engine. In this way the humidity of the compressed intake air is increased at elevated pressure level to a higher humidity level. Additionally, operation of a heat exchanger provided in an intake air conduit controls the temperature of the compressed intake air supplied to an air intake chamber. The operation of the heat exchanger and/or the injection of the water is controlled by means of a control arrangement based on the measurement of air conditions in the air intake chamber.

[0013] The measurement of air conditions preferably comprises measuring at least the temperature and humidity of the air and advantageously also involves air pressure measurement. It is possible to store operating information of the heat exchanger required for a certain amount of water injection and distribution of water between different nozzles as recipe information in the control arrangement.

[0014] Favourably heat is supplied to the compressed intake air before being supplied to the cylinders of the engine in such a manner that the introduced or injected water is evaporated, whereby it is possible to achieve very small nitrogen oxide emissions. Water is conveniently fed into the combustion air in several stages and the temperature of the compressed intake air is changed between the stages.

[0015] Water may be fed into each cylinder of the engine in order to further decrease nitrogen oxide emissions particularly at partial loads. This water is favourably fed into the cylinders in addition to the water fed into the intake air.

[0016] Conveniently a first amount of water is first introduced into the compressed intake air and heat is supplied to the intake air during or after the water injection and, additionally, a second amount of water is further introduced into the compressed intake air after the additional heat has been supplied to the intake air. The second amount of water may be introduced into the intake air or directly into the combustion chamber of the engine. Favourably the first amount of water is such that it utilises the heat of the compressed intake air so that the temperature of the intake air decreases below 85°C.

[0017] Suitably the method of the invention is specifically advantageously realised so that heat is transferred as required to the intake air from a cooling system of the engine in order heat the moist intake air. In addition a third amount of water may be fed into each cylinder of the engine for further decreasing nitrogen oxide emissions. The third amount of water is fed into each cylinder of the engine particularly favourably while the engine is running at partial load, typically below 40-60% load. Preferably in the method according to the invention water is injected in total at a rate of 200-600 g per kWh-unit produced by the engine. In this way it is possible to achieve very low nitrogen oxide emissions and simultaneously to maintain optimised operation of the engine. Also unnecessary condensation of water vapour can be minimised.

[0018] Preferably introduction of water to the compressed intake air and to the cylinders (i.e. the first, second and third amounts of water injected) is controlled based on at least one of the following values measured and/or defined while the engine is running: temperature and humidity of ambient air used by the engine; temperature and humidity of intake air of the engine; load and/or rotational speed of the engine; amount of nitrogen oxides in the exhaust gases; and visible smoke of exhaust gases. Advantageously, the amount of water fed at each temperature and pressure level is such that the humidity of air increases up to at least 70%-100% humidity level.

[0019] According to another aspect of the present invention there is provided a supercharged piston engine arrangement for reducing nitrogen oxide emissions comprising a piston engine, a supercharger in connection with each cylinder of the engine through intake air conduit means and a nozzle arrangement in connection with the intake air conduit means for feeding water in to the intake air, wherein a heat exchanger is provided in connection with the intake air conduit means for supplying heat to the intake air. Advantageously the heat exchanger is connectable with cooling system of the engine. Additionally the engine comprises a direct water injection arrangement for each cylinder. Advantageously the heat exchanger is constructed as an integral part of the engine.

[0020] By means of the invention, an advantageous arrangement is accomplished with respect to both the reduction of nitrogen oxides and the flexible operation of the engine whereby nitrogen oxide emissions are minimised in all operating circumstances of the engine. Additionally, with the arrangement of the invention, it is possible to run the engine without using water injections if so desired. With the arrangement of the invention most often it is possible to avoid using a separate NOx-catalyser, which considerably reduces space requirement.

[0021] Embodiments of the invention will now be described, by the way of example only, with particular reference to the accompanying drawings, in which:

Figure 1 illustrates a schematic view of a preferred embodiment of the invention; and

Figure 2 graphically illustrates in a schematic manner heat balance according to the water feeding arrangement of Figure 1.

[0022] Figure 1 shows a piston engine generally designated by the reference numeral 1 connected to an exhaust gas supercharger 2 in a manner known as such.

A nozzle arrangement 4,4' for feeding water into inlet or intake air is arranged in a conduit 3 which is an extension of, or a portion of, a conduit connecting the supercharger 2 and the engine. In order to change the temperature of the intake air, a heat exchanger arrangement 5,5' is also arranged in the conduit 3. The conduit 3 is connected to an air chamber 3' of the engine 1 from which air is led into each cylinder of the engine. The heat exchanger arrangement preferably comprises two distinct heat exchangers 5 and 5'. In Figure 1 a droplet separator 16 is also shown which may be installed if so desired. Coupling of the heat exchangers 5,5' in Figure 1 is only exemplary. As an alternative coupling (not shown), the heat exchangers may be connected in separate flow circuits. Preferably, the heat exchangers are integrated into the structure of the engine or as a part of the air chamber 3' or even as a part of the body of the engine. Additionally the arrangement comprises a connection to a cooling system 14 of the engine 1, whereby heat from cooling of the engine can be transferred to the intake air. This connection or coupling may be realised alternatively by a flow channel arrangement internal to the engine.

[0023] The engine arrangement of Figure 1 also comprises a source of water 6 which may vary according to the application of the engine. In a ship's engine the water may be properly treated seawater originating from the water on which the ship sails. In other cases the water may be taken from a water distribution pipe system. The source of water 6 is connected by ducting 7 to a nozzle arrangement 4,4' provided in the channel 3 and by ducting 7' to an injection arrangement, such as a nozzle 8, arranged in association with each cylinder. In this context by "water" is meant pure water or water containing solution.

[0024] The engine arrangement also comprises measuring probes 9,9' for measuring operating parameters or conditions, such as the temperature and humidity of the intake air, and arranged in the conduit 3 both before and after processing the intake air. A probe 10 for defining the state of operation, such as the load and/or speed, of the engine as well as a probe 11 for defining the state, such as the amount of nitrogen oxides and/or of visible smoke, of the exhaust gases are also provided. Additionally, it is possible to provide a probe 9" for measuring the condition of intake air before it is compressed in the supercharger 2. These aforementioned probes are connected to a control arrangement 12 which controls the operation of each water introducing or injecting means 4,4',8 in predefined manner based on the measurements. The control arrangement 12 may be a separate or integral part of control system of the engine. The control arrangement 12 is also in connection with a valve arrangement 15 by means of which the coupling or operation of heat exchangers 5,5' can be altered according to whether the intake air needs to be warmed or cooled. In the embodiment illustrated cooling takes place by connecting the heat exchangers to a supply of cooling medium 13.

[0025] In the arrangement according to Figure 1 while the piston engine is running intake air is led through the supercharger 2 where it is compressed and is then fed by means of the conduit 3 into the engine. The pressure of the intake air is increased from ambient pressure to an elevated pressure level in the supercharger 2. In the conduit 3 or before leading the air into the engine, water is fed into the compressed intake air by means of nozzles 4 thereby increasing the humidity of the intake air. After the introduction of the water into the intake air by means of the nozzles 4, the temperature of the compressed intake air is altered with the assistance of the heat exchanger 5,5' depending on circumstances. The amount of water to be fed depends in turn, for example, on the desired reduction level of nitrogen oxides.

[0026] According a certain operating mode of the method of the invention, a first amount of water is fed at a first stage by nozzle 4 to the compressed intake air under control of the control arrangement 12 as a result of which the temperature of the intake air decreases and its humidity increases. After or during this stage, heat is supplied to the compressed intake air by means of the heat exchanger 5,5' and the temperature of the intake air is increased. Additionally, while the engine is running in partial load, a third amount of water is fed or injected into each cylinder of the engine by nozzles 8. Advantageously, when the load of the engine is less than 40-60%, water is fed directly to each cylinder of the engine in addition to being fed into the intake air.

[0027] It is possible for a second amount of water also to be supplied to the compressed intake air by means of nozzle 4' depending on the circumstances. In this operating mode heat is supplied to the humid intake air from the cooling system 14 of the engine. The first amount of water is adapted to be such that the air cools down preferably to at least about 85°C.

[0028] In Figure 2 there is shown by way of example a heat balance of the water feeding arrangement in such a manner that the y-axis depicts heat power balance and the x-axis depicts the load of the engine in percentage terms. Above the zero level each unit process is exothermal and below the zero level it requires additional heat.

[0029] Referring to Figures 1 and 2 according to another operating mode of the invention, in a method of reducing nitrogen oxide (NOx) emissions of a supercharged piston engine, a control arrangement 12 defines and delivers control commands regularly based on predetermined set values and measurements obtained from probes 9,9',9", 10 and 11 measuring inter alia the condition of air, the engine load and/or the engine speed, as well as the NOx-content of exhaust gases and/or the amount of visible smoke. By means of control commands delivered by the control arrangement 12, the distribution and amount of water to different nozzles 4,4',8 is controlled together with the control of the operation of the heat exchangers 5,5' in order to control the

temperature of the intake air.

[0030] In the control arrangement 12 there is stored, as set values, certain reduction levels of nitrogen oxide (NOx) which correspond to a certain reduction level compared with a situation where the method of the invention would not be utilised. The curves 20,21,22 in Figure 2 represent these reduction levels as a function of engine load. The control arrangement 12 defines a water injection requirement corresponding to each reduction set level of nitrogen oxide and engine load or speed, as well as the feeding ratio of water to different nozzles 4,4',8. Based on this information the control arrangement 12 controls the nozzles for injecting the desired amount of water. The control arrangement 12 also controls the operation of the heat exchangers 5,5' based on information measured by the intake air probes 9,9' as will be explained in the following. When the heat content of the compressed intake air corresponds with or exceeds the heat required by the amount of water injected by the nozzles 4,4' and/or when the intake air temperature exceeds a set value, the control arrangement controls the heat exchanger 5,5' to cool the air. This situation corresponds in Figure 2 to the nitrogen oxide reduction level depicted by curve 22 at a load of the engine over about 75%. In this region the process is exothermal. In the example illustrated, curve 22 corresponds to about a 65% reduction of nitrogen oxides with a certain type of engine. In the situation where the heat of the intake air is lower than the heat required by the amount of water injected by nozzles 4,4' and/or the temperature of the intake air to be fed into the engine at the probe 9 is below its set value, the control arrangement 12 controls the heat exchanger to heat the air. Advantageously this is accomplished so that the control arrangement 12 of the engine couples the heat exchangers 5,5' of Figure 1 to the cooling system 14 of the engine 1 by means of valve arrangement 15. This situation corresponds in the presentation of Figure 2, for example, to the reduction level depicted by curve 21 being 40-95% of the load area of the engine. The curve 21 corresponds to an 80% nitrogen oxide reduction level. When the control arrangement during continuous operation defines the situation to be such that the heat of the intake air is less than the heat required by the water injected by nozzles 4,4' and simultaneously the heat extracted from the engine's cooling system 14 exceeds a certain set value, the control arrangement restricts the amount of water injected through nozzles 4,4' to the intake air to the prevailing amount and controls possible additionally required water injection to be injected through the nozzles 8 directly to the cylinders of the engine. This situation corresponds in Figure 2, for example, to the reduction level depicted by curve 20, being the load area below 60% of engine 1. In this load area the heat 23 usable from the cooling system of the engine is less that the total amount of water corresponding to the curve 20 would require. The curve 20 corresponds to a 90% nitrogen oxide reduction level. Thus, by operating as outlined above, a very high reduction in the nitrogen oxides' content of the exhaust gases is obtained also at partial loads of the engine.

[0031] The invention is not limited to the practical applications and numerical values shown but several modifications of the invention are reasonable within the scope of the attached claims.

Claims

1. A method of reducing nitrogen oxide (NOx) emissions of a supercharged piston engine (1), comprising compressing intake air to produce compressed intake air, introducing water (4,4',8) into the compressed intake air to increase the humidity of the intake air, and supplying the humidified and compressed intake air to the engine, **characterised in that** the temperature of the compressed intake air, in addition to being influenced by the introduction of water, is controlled by being passed through heat exchanger means (5,5') before being supplied to the engine.

2. A method according to claim 1, **characterised in that** the intake air is supplied to an air chamber (3') before being supplied to cylinders of the engine, and **in that** operation of the heat exchanger means is controlled by a control arrangement based on the measurement of air condition in the air chamber (3').

3. A method according to claim 1 or 2, **characterised in that** the compressed intake air is heated before being supplied to the engine so as to evaporate the introduced water.

4. A method according to claim 3, **characterised in that** a first amount of water (4) is introduced into the compressed intake air before or during said heating of the compressed intake air, and **in that** a second amount of water (4') is introduced into the compressed intake air after said heating of the compressed intake air.

5. A method according to claim 4, **characterised in that** the introduction of said first amount of water decreases the temperature of the compressed intake air to below 85°C.

6. A method according to claim 3 or 4, **characterised in that** heat is transferred to the compressed intake air from a cooling system of the engine (1).

7. A method according to any one of the preceding claims, **characterised in that** water (8) is fed into each cylinder of the engine for further decreasing nitrogen oxide emissions.

8. A method according to claim 7, **characterised in that** the water (8) fed into each cylinder of the engine is fed into the cylinders while the engine is running at partial load and is fed in addition to the water fed into the compressed intake air.

9. A method according to claim 8, **characterised in that** water is fed directly into each cylinder of the engine while the load of the engine (1) is less than 60% load, preferably less than 40% load.

10. A method according to any one of the preceding claims, **characterised in that** the total amount of water is introduced at a rate of 200-600 g per kWh-unit produced by the engine.

11. A method according to claim 8 or 9 or claim 10 when dependent on claim 8 or 9, **characterised in that** the introduction of water to the compressed intake air and to the cylinders is controlled based on at least one of the following values measured and/or defined while the engine (1) is running: temperature and humidity (9") of ambient air used by the engine; temperature and humidity (9',9') of the compressed intake air of the engine; load and/or rotational speed (10) of the engine; amount of nitrogen oxides in exhaust gases from the engine; and visible smoke of exhaust gases (11) from the engine.

12. A method according to any one of the preceding claims, **characterised in that** the amount of water introduced into the compressed intake air at a particular temperature and pressure increases the humidity of the compressed intake air up to at least a 70%-100% humidity level.

13. A supercharged piston engine (1) comprising cylinders, a supercharger (2) for compressing intake air, conduit means (3) connecting the supercharger to said cylinders for supplying compressed intake air from the supercharger to said cylinders, and a nozzle arrangement (4,4') associated with the conduit means (3) for introducing water into compressed intake air passing through the conduit means (3) to said cylinders, **characterised in that** heat exchanger means is associated with the conduit means (3) to heat compressed intake air passing through the conduit means.

14. An engine according to claim 13, **characterised in that** the heat exchanger means (5,5') is connectable with an engine cooling system (14).

15. An engine according to claim 13 or 14, **characterised in that** the engine (1) further comprises a water injection arrangement (8) for injecting water directly into each cylinder.

16. An engine according to claim 13, 14 or 15, **characterised in that** the heat exchanger means (5,5') comprises an integral part of the construction of the engine (1)

17. An engine according to any one of claims 13 to 16, **characterised in that** said nozzle arrangement (4,4') comprises nozzles arranged to feed water into the compressed intake air both before and after the heat exchanger means (5,5') in the air flow direction.

18. An engine according to any one of claims 13 to 16, **characterised in that** the nozzle arrangement (4,4') comprises several nozzles operable independently to introduce water into the compressed intake air as required.

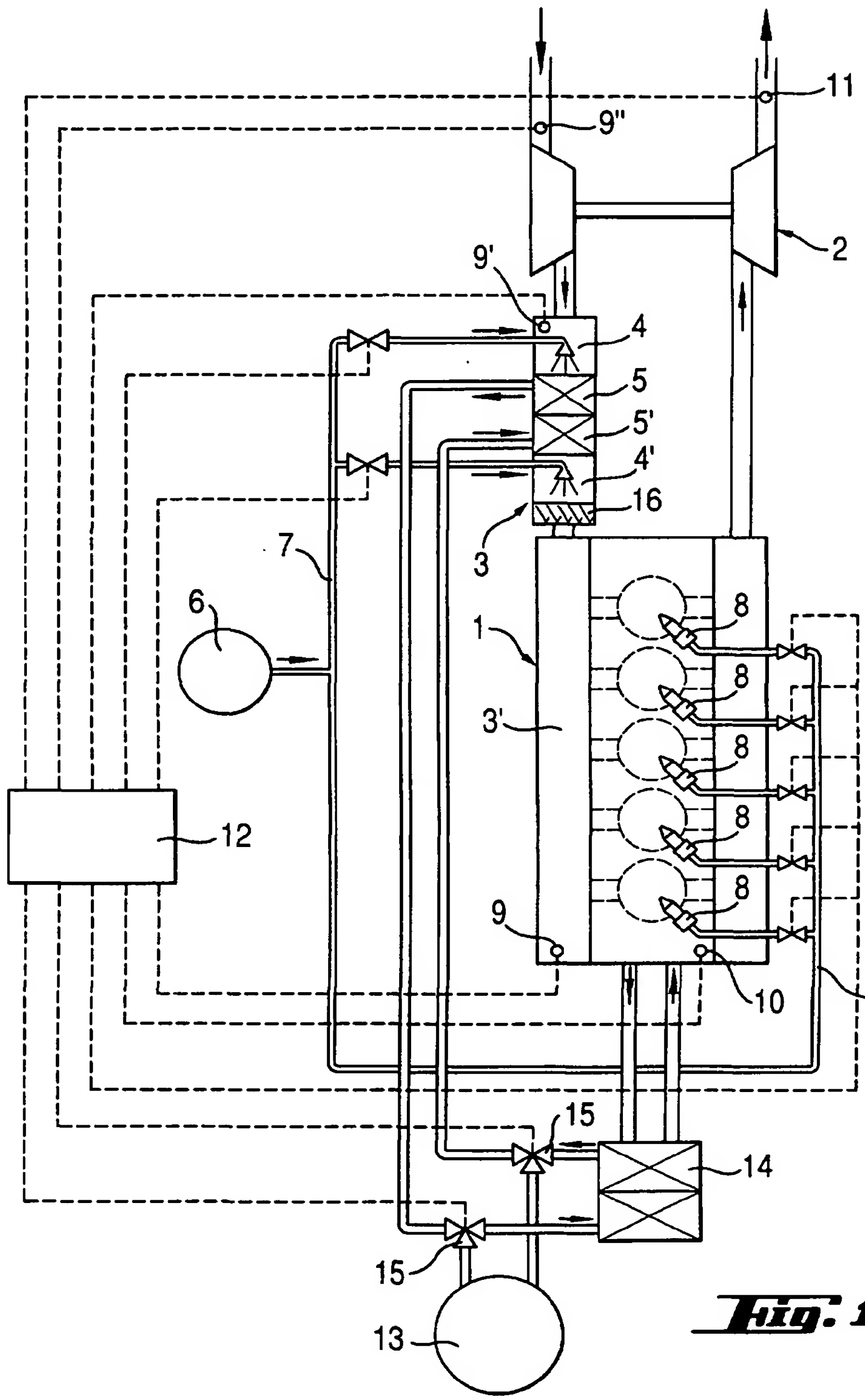

Fig. 1

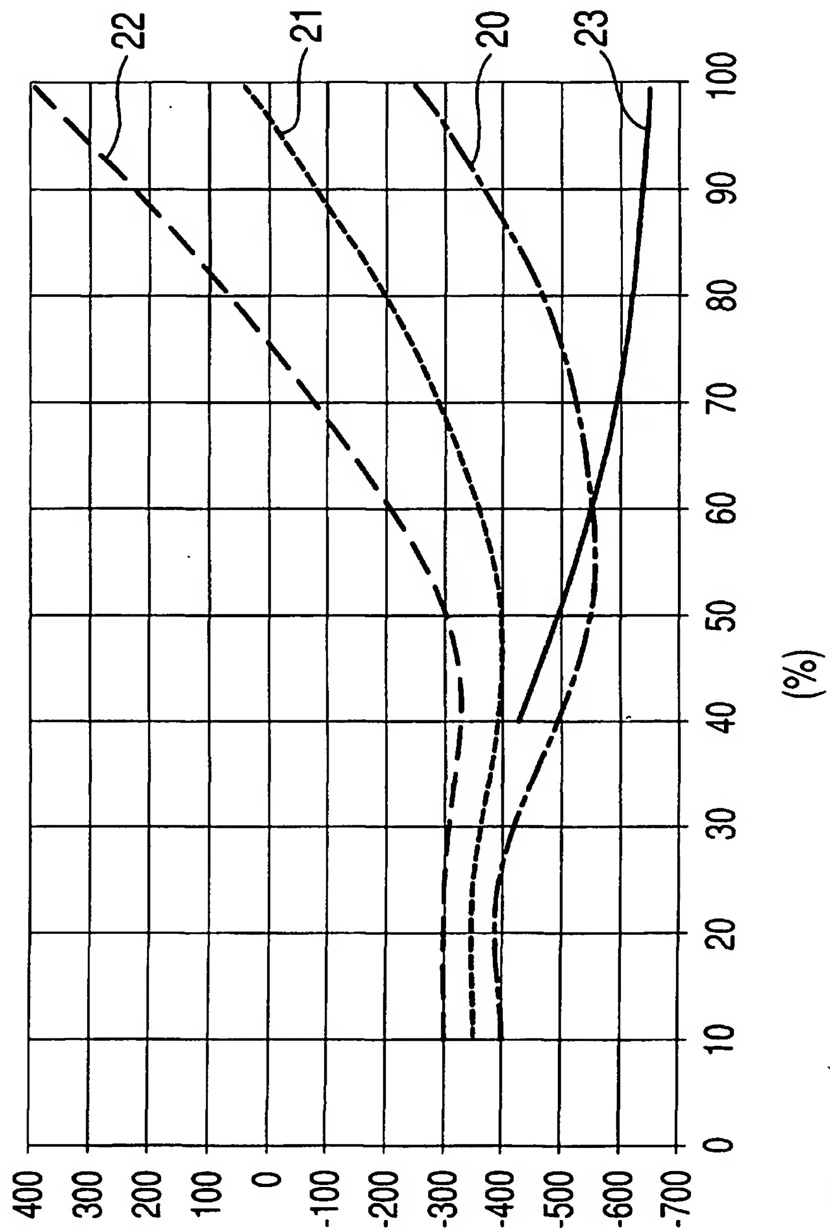
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Fig. 2